

Work-hardening of Ferrite Head Surfaces by Wear with Flexible Recording Media

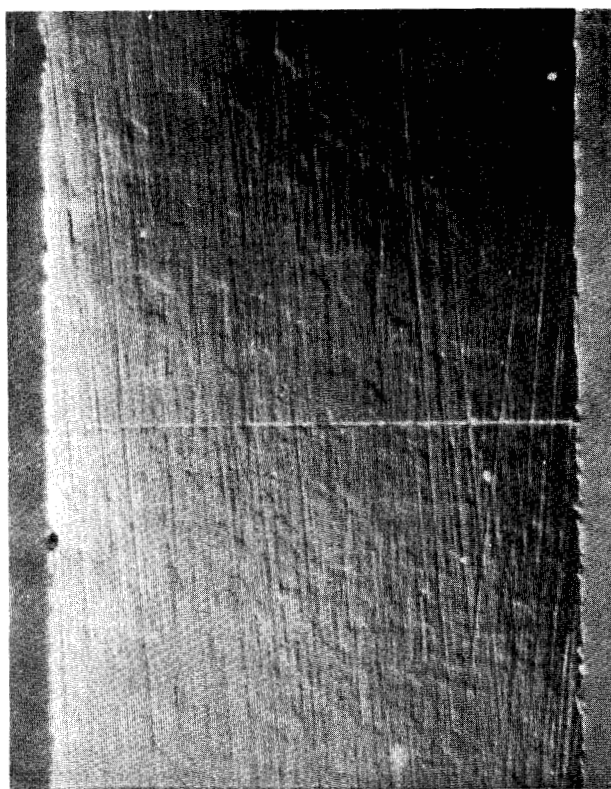
Abstract: The ferrite surfaces of rotating magnetic heads were found to have been work-hardened to different degrees depending upon the abrasiveness of the flexible recording media used. For the more abrasive tape, the work-hardening was less than for the less abrasive tape. Associated with the increase in microhardness was decreased signal read-back and increased incidence of surface "pull-outs." These phenomena may be understood in the context of fracture mechanics where residual stress, resulting from plastic deformation of the ferrite, is predominant in the wear mechanism.

Introduction

The extensive application of ceramic materials in the running surfaces of magnetic recording heads under conditions of continuous or intermittent contact with recording media demands development of a better understanding of the mechanism of the wear process. The nature of the tribology system requires emphasis on the rate of abrasion of the transducer surface because design constraints allow for only a small amount of dimensional change. The kind of ceramic used for recording head applications has to be magnetic and most commonly is manganese zinc (MnZn) or nickel zinc (NiZn) ferrite. Polycrystalline forms can be formed by methods which produce bodies of high density, low porosity, and high strength with controlled microstructure, i.e., grain size. Wear resistance appears to decrease as the grain size becomes smaller [1, 2]. That trend for NiZn ferrite is reported by Kehr to extend down to a 3.5 μm average grain size despite increases of bulk strength [3]. Mn-Zn ferrite may be made as single crystals which enhance the wear resistance of that material quite substantially [1, 4]. Improved polycrystalline ferrites are available from hot-pressing and precision cold-pressing-sintering techniques which seem to give comparable wear performance to single-crystal material [4]. Unfortunately, it is often difficult to compare published values of head wear because it has been evaluated in a wide variety of environments dependent upon the application of interest, e.g., video, audio, data processing, or instrumentation equipment. In the work reported by Kehr [3], wear of rods by CrO_2 tape was about $3\times$ greater than that by a $\gamma\text{-Fe}_2\text{O}_3$ tape. Others have used

lapping tapes [5] or have wear-tested on specific equipment relating to the product applications [4, 6]. The trend of development in applications has been toward higher relative speeds and more frequent "in contact" conditions between the rubbing head and media surfaces. This results in what has been generally considered as an abrasive wear situation. Efforts to shed light on the mechanism of the wear process for the brittle, hard ferrite have been reported quite recently. Yamada [7] proposed that the head surface is microscopically scratched in a brittle manner by the acicular particles (of the magnetic pigment) and is macroscopically removed in a brittle manner as stripes or islands, depending on the smoothness of the tape surface. Using fracture mechanics principles, he related head wear inversely to the square root of the Knoop microhardness of the head material. Potgiesser [8] observed that the first sign of wear is the appearance of very small scratches on the head surface and found that such scratches have an associated compressive strain field around them resulting in the formation of a surface layer with disturbed magnetic properties. Kugimiya [9] explained differences in wear and crumbling of the ferrite to be partly due to the stability of grain boundaries, induced by the orientation of neighboring grains, and the easy abrasion of certain planes resulting in a small stress buildup. Working with single-crystal MnZn material with rubbing by a slider, Tanaka [10] found that the upper surface layer was much deformed and more work-hardened as compared to the undeformed subsurface layer. Broese van Groenou [11] discussed the grinding of fer-

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(a)



(b)

Figure 1 (a) A typical lapped and unworn ferrite surface (304 $\times$); (b) a worn ferrite surface (304 $\times$).

rites and concluded that the main modes of material deformation were well established and that smearing and brittle modes are found side by side. Lawn [12] described a model for the wear of brittle materials which developed some interesting implications: he anticipates a brittle-to-ductile, chipping-to-ploughing transition in the wear mechanism at low loads and small particle sizes with an attendant fall in wear rate to a value typical of nonbrittle solids. Sheldon [13] concluded that for erosive wear of work-hardenable metals, the best correlations were obtained when the hardness value was measured on the eroded surface. This paper shows that it is possible to integrate these elements into an overall conceptual model to describe phenomena associated with the wear of ferrite heads in a data processing environment.

Environment and phenomena observed

The environment essentially was a rotating head, as found in the data recording device unit of an IBM 3850 Mass Storage System, where cartridge, flexible recording media were used. It was helically scanned, with a sequence of operations involving load, thread, step to stripe 9000, with a revolution each step, rewind and unload. The relative velocity in the head-tape interface was 1000 ips (25.4 m/s). Standard head contours and tape tensions

were employed resulting in an average spacing of 8 μ in. under ambient conditions of temperature (21°C, 70°F) and relative humidity (20–50%). The duration (400–1200 h) of the wear tests was sufficiently long as to make a dimensional change measurable by profilometer techniques with reasonable confidence. Two recording media samples provided a ratio ranging from about 2:1 to 3:1 in abrasivity and enough of a perturbation for the system for a useful range of response. The original “unworn” condition of the ferrite surface was chosen to be that obtained by polishing with flexible abrasive lapping tape as described later. A typical lapped and “unworn” ferrite surface is shown in Fig. 1(a). The grain faceting is enhanced by a differential interference contrast (Nomarski) technique. The average grain size of the NiZn ferrite is of the order of 9 μ m. Note also the scratching in the form of small-scale ductile grooving. The signal output from this head surface is considered to be the 100% reference point. The rate of material removal by such a tape lapping process is several orders of magnitude higher than for the recording media.

In Fig. 1(b), a “worn” surface, we can see the variety of features which have developed in addition to those noted previously. Away from the edges, there are small localized regions where fracture and rupture have oc-



Figure 2 Pull-out region (1250 $\times$).

curred as a result of crack propagation in directions roughly perpendicular to the plane of working surface. Such regions are commonly called "pull-outs." Also note plastic flow in a direction approximately at right angles to the direction of relative motion.

At the higher magnifications convenient to an SEM, in Fig. 2 a pull-out is seen to have edges with an ordered geometry characteristic resulting from intergranular crack propagation and intersection.

Debris which originates from these regions causes very small scale plastic deformation and grooving, as is shown clearly in Fig. 3. Such regions also collect debris originating from the media. This and crack propagation which has not yet resulted in a pull-out are shown in Fig. 4.

The above are submitted as evidence for the presence of competing fracture processes during the removal of the brittle material. A summary of the signal output comparisons and the observations of the surface features associated with various processes is found in Table 1.

The key aspect which should be noted is the virtually complete absence of pull-out features with dry abrasive tape lapping, with the tendency for an increased incidence of that feature as the removal rate decreased. Apparently one of the fracture mechanisms suppressed and dominated the other competing processes in the regime

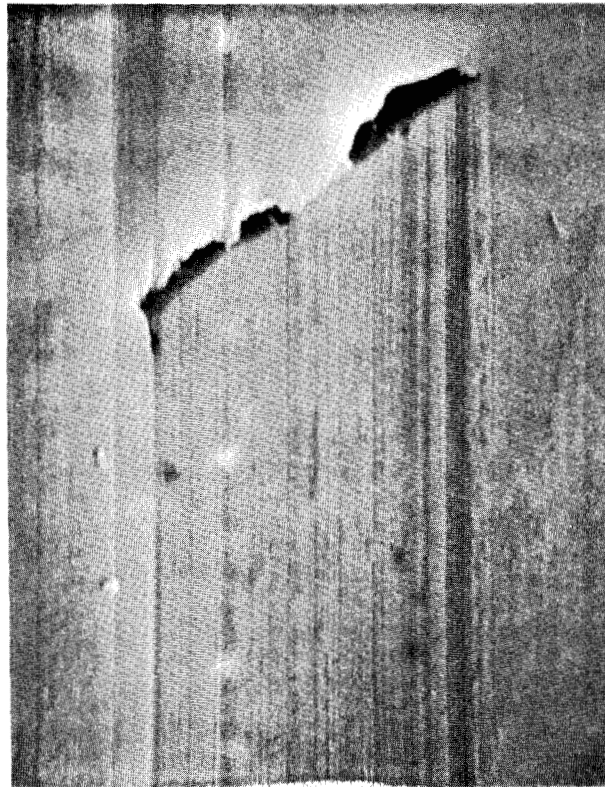


Figure 3 Pull-out scratch showing plastic deformation and grooving (5000 $\times$).

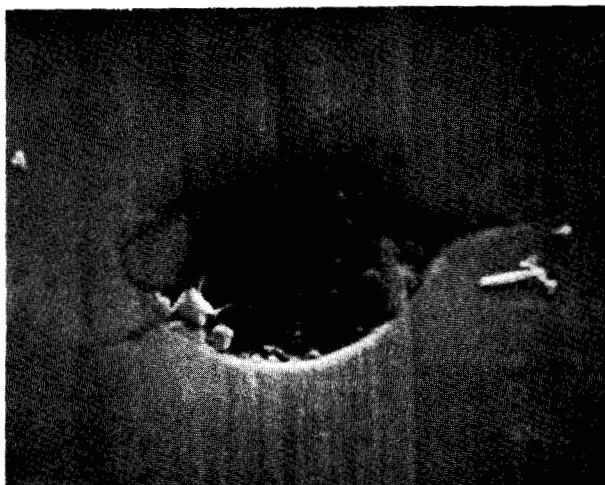


Figure 4 Pull-out region showing debris and crack propagation (20 000 $\times$).

examined. Signal degradation developed more rapidly than the dominant features, suggesting sensitivity to micro-scale events. In contrast, pull-out characteristics often appeared much later.

Table 1 Summary of signal output comparisons and observations for various wear tests.

Surface	Removal rate	Signal remaining (%)	Dominant features
Unworn (lapped)	High	100	Grain relief, grooving
Worn	Low	90-95	Above and a few pull-outs
Worn	Very low	60-80	Above and many pull-outs
Worn then lapped	High	95-100	Grain relief, grooving

Table 2 Microhardness of ferrite head surfaces. For removal rates, the total material removed ranged from 5 to 10 μm in depth. The load used was 10 gf.

Surface	Removal rate	Knoop microhardness (kg/mm^2)
Unworn (lapped) heads	High	920-970
Worn head A	Low	1020-1060
Worn head B	Very low	1100-1300
Worn head B, then lapped, removing 1.25 μm and indents	High	920-970

Stokes [14] reviewed the effects of mechanical finishing operations, especially machining, on ceramics and listed the features produced by brittle fracture mode as surface roughness, surface cracking, and grain pull-out. The origin of these lay in either transgranular or intergranular fracture processes with greater dependence on intergranular crack rupture of isolated surface grains for pull-outs. He mentioned that residual stresses resulted from plastic flow and cited a specific example of a magnetic material thus affected. For the nickel-zinc ferrite of interest, Thornley [15] has found that application of an external axial compressive stress of the order of 280-560 kg/cm^2 (4-8000 psi) resulted in a reduction of permeability as great as 60-80%. Due to the difficulties of annealing assembled ferrite heads and the observation by magneto-optic means [16] that a disturbed magnetic layer is formed even by tape lapping, it became apparent that a quantitative *in situ* technique was desirable for physical characterization of the state of the surface of worn heads in a quantitative manner.

Hardness of a material is generally considered to be its resistance to deformation. Micro-hardness is especially pertinent for hard, brittle materials, such as ferrite, if the loads for forming indentations are sufficiently low as to avoid cracking, because crack propagation may be considered as a form of internal stress relief. A Knoop diamond pyramid indenter is especially suitable by virtue of

its shape, creating indentations which are extremely shallow in depth compared to their length. The techniques are straightforward and are standardized (ASTM E-384). It was reasoned that if the loads were kept low enough, the measured micro-hardness of various worn ferrite head surfaces would yield further insight into the underlying mechanism of the wear process, through an evaluation of residual stress by mechanical means.

Experimental procedures

It was found most convenient to remove the heads from the rotor used to support them, for examination and hardness determinations. Due to the contour design used, there was ample room to place a sufficient number of indents in the worn surface to obtain consistent and significant measurements. Generally, ten readings of five indents gave an estimate of the standard error of 28 kg/mm^2 with a 99% confidence interval. A Tukon Model MO microhardness tester was used, which employed a diamond Knoop indenter loaded with dead weights ranging from 1 to 500 gf. Loads of 10-25 gf were used following an evaluation of indents made in the range of 2 to 500 gf. The criterion for selection was the maximum calculated Knoop hardness. Ambient conditions in the laboratory were $21 \pm 1^\circ\text{C}$ ($72 \pm 2^\circ\text{F}$) and $35 \pm 15\%$ R.H. at the time of measurements. Knoop indentations have a ratio of diagonals of 7:1, with the longest diagonal-to-depth ratio of about 33:1. The length of the indents was of the order of 11-13 μm corresponding to depths of 0.33-0.39 μm or about 13 to 16 μin . Indents of 10 gf often fit comfortably within grain boundaries for the particular ferrite used despite the fact that the distribution of grain sizes was found to be log normal. Hardness determinations on worn head surfaces were made after wear testing was completed.

Abrasive tape lapping was carried out using Imperial® [17] grade lapping tape, 0.5 μm nominal size Cr_2O_3 particles on a 1.0-mil-thick backing substrate, for a time necessary to remove $\approx 50 \mu\text{in}$. from the surface. The media used were typical of those available for data processing applications. The results of the microhardness determinations are summarized in Table 2.

The hardness levels reported were all measured with a 10 gf load and were attained at steady state abrasive wear conditions established in times fully an order of magnitude larger than those associated with the development of signal degradation. The observations coupled with these data would negate the concept that pull-outs serve to implement signal degradation by separation effects. This time dependence similarly would seem to eliminate thermal causes.

The results show clearly that work-hardening of the ferrite has taken place on the worn surfaces and that the extent of the work-hardening effect depends upon the wear rate, which in turn reflects a shift from a mechanism

dominated by transgranular fracture to one dominated by intergranular fracture. A flat polished sample, fully annealed, had a range of 700–750 HK_{10} . It is obvious that an increase in Knoop microhardness of the magnitude of 200–350 kg/mm^2 is a significant indication of large residual stress levels in the near-surface regions of worn ferrite surfaces. Note also that the depth of the affected layer is less than 50 μin .

Discussion

With brittle solids, material is removed mainly by the propagation and intersection of cracks. The extent of cracking can be localized by the presence of very small (submicron) abrasive grains. For such processes (abrasive wear, grinding, polishing, lapping) fracture is involved under the small, hard particles which are loaded by various combinations of normal and tangential forces. It is well known that as smaller particles are used, a finishing process becomes more inefficient and eventually causes brittle solids to behave in a completely ductile manner. Practical phenomena that usually involve indentation in the plastic regime are hardness measurements and abrasive wear. Indentation fracture involves both surface (radial) and subsurface (lateral) crack propagation modes. Material removal by a plastic deformation mechanism is characterized by lateral crack extension to grain boundaries. Crack arrest in these regions, with subsequent extension along the boundaries and intersection with other cracks, results in pull-outs. Observations of such fracture indicate that the subsurface cracks are a major source of material removal. Grain size dependence can be related to the change in the extent of lateral fracture needed with coarse-grained material. The plastically deformed zone and related lateral cracks may be contained within single grains, whereas with fine-grained material these extend through several grains. Thus, we have a transition in "effective" fracture toughness (K_{IC}) and hardness (H) with grain size changes. It is fracture toughness and hardness, respectively, which control crack propagation and plastic indentation. Lawn [18] has put together a physical model, based on fracture mechanics, to describe chipping fracture. The picture that is developed is shown schematically in Fig. 5.

When an indenter is loaded on the surface of a brittle solid, a confined zone of plastic (irreversible) deformation is formed about sharp points or corners, from which surface cracks initiate and subsequently propagate. During unloading, the surface cracks close, but just prior to complete removal of the load, subsurface cracks initiate and extend laterally and upward toward the surface. It is evident from microscopic examination that the driving force for lateral crack propagation originates from a residual stress field associated with the plastic deformation zone. The stress levels achieved beneath indenters in hardness

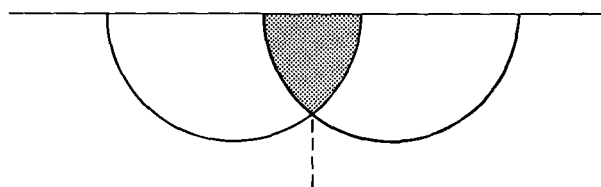


Figure 5 Fracture geometry under sharp indenter, section (after Lawn [18]).

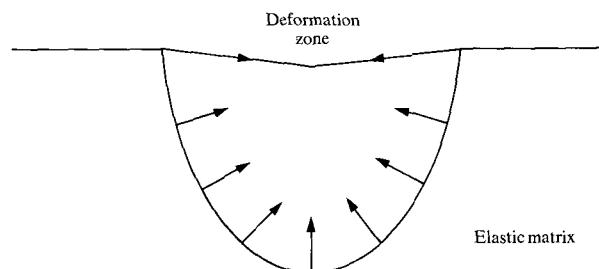


Figure 6 Schematic of distribution of residual contraction after indenter withdrawal (after Lawn [18]).

tests on highly brittle solids tend to be of the order of the intrinsic bond strength of the structure. The resulting effect is shown schematically in Fig. 6.

Lawn envisions such a model as providing a physical insight into the wear of brittle materials resulting from what may be considered as a summation of many localized, brittle microfracture events. Thus, the cumulative effect of many scratches formed in the plastic regime introduces considerable surface compression stress, which is balanced by tensile stress in the bulk of the specimen to preserve mechanical equilibrium. Irreversible damage, as in cracks, cannot be removed by annealing. Reversible damage from residual stresses can be recovered by annealing. Scratches formed by the sharp, angular shapes of abrading particles may generate their own surface flaws which serve as fracture initiation sites growing under the influence of and within highly localized stress fields. Blunt-edge conditions tend more to be affected by pre-existing flaws. It appears that the wear rate is uniquely determined by material hardness, which controls the scale of the deformations. The extent of the crack patterns beneath the wearing particles may be such that the toughness properties are important to the abrasion process.

Now, on the basis of observations of plastic deformation/grooving, signal output degradation, grain-faceting, pull-outs, and quantitative microhardness data on worn ferrite head surfaces, we have a fracture mechanics picture for the wear process. Unfortunately, the attributes of the low-wear-rate regime include residual stresses from plastic deformation of the worn surfaces which create a

magnetic "dead" layer, increasing the effective spacing, thus reducing signal output. Conversely, the high-wear regime reduces this effect at the cost of reduced head life. In certain applications, e.g., video recording, rates of wear typically are an order of magnitude greater than those experienced here, and replacement of heads is expected. For other situations, the important question is: Are we limited to high-wear-rate regimes for high density magnetic recording with ferrite head materials? Efforts to reduce the wear rate by reducing contact stresses may be largely self-defeating for applications where head/tape separations must be less than 5 μ in. Optimization of the design of the magnetic head circuit and the magnetic material to accommodate the existence of the residual stresses in a low-wear-rate regime appears to be essential.

Evans [19] has proposed a proportionality for impact wear of brittle materials as follows:

$$\text{Volume material removed} = \alpha \frac{P^{\frac{7}{6}} L}{K_c^{\frac{2}{3}} H^{\frac{1}{2}}},$$

where K_c = fracture toughness, H = hardness, P = load, and L = sliding distance. It is a matter of speculation whether the relationship involving fracture toughness for ferrite can be affected enough by composition variations within a given material system. Perhaps it is more sensitive to the system (i.e., NiZn ferrite vs MnZn ferrite). More important, however, is the consideration of a relatively large grain size, which, for a given abrasive environment, effectively increases toughness by the expedient of forcing crack extension to take more transgranular paths rather than an easier (energy-wise) intergranular path, though elimination of all grain boundaries (monocrystals) may permit catastrophic crack propagation. In addition, the accelerating effect of humidity on wear may be accounted for on the basis of moisture-enhanced crack propagation, i.e., stress corrosion. Lastly, the values for the material hardness and toughness must be those for a worn surface, not for the bulk annealed condition. It is therefore appropriate to suggest that these issues be considered in detail in the future.

Summary

The abrasive wear of NiZn ferrite in a magnetic tape low-wear regime was found to be characterized by a plastic flow mechanism resulting in considerable work-hardening of the near surfaces. The origin of the work-hardening effect is in residual compressive stresses which also cause the formation of a magnetically "dead" surface layer and shift the crack rupture pattern from a largely transgranular to an intergranular fracture mode featuring plastic deformation effects. A paradox was noted for the optimization of such a tribological system as applied to high

density recording, namely, that low wear rates corresponded to greater effective magnetic separation despite reduced physical spacing between the rubbing interfaces. To fight this tendency, it would appear that high head wear rates must be accommodated to maximize signal output from this type of ferrite head. It is suggested that prediction of wear rates involving ferrite materials should incorporate fracture toughness and low-load microhardness as measured with worn surfaces.

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